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AN EXPERIMENT ON PARTICULATE DAMPING IN A TWO-DIMENSIONAL HYDROGEN-OXYGEN COMBUSTOR

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ABSTRACT

Aluminum particles (5μ mean diameter) were injected into a small circular combustor by a secondary flow process used for transverse mode stability rating. Small mass concentrations of aluminum were found to be effective in suppressing instability. A critical concentration of 2/100 percent was noted below which the effect was destabilizing.

INTRODUCTION

The addition of small fractions of aluminum powder to the composition of solid propellants is an effective method of suppressing combustion instability in many engine configurations. This suppressive action was demonstrated in tests with a small two-dimensional circular combustor (1) where a one-half percent mass addition of aluminum suppressed instability over a broad range of test conditions which were increasingly unstable without aluminum. Also, secondary injection of aluminum particles produced the same suppressive effect as when it was incorporated in the propellant grain. It was concluded that the suppressive action occurs in the gas phase above the burning surface rather than altering surface reactions and that particulate damping is the stabilizing mechanism.

With particulate damping as the stabilizing mechanism the injection of aluminum should be equally effective in suppressing instability in liquid and solid propellant combustors. The sensitivity of the two-dimensional circular combustor to small fractions of aluminum and the availability of a liquid propellant version of this combustor prompted this experiment. Aluminum particles were introduced by a secondary flow process similar to that used in the solid propellant tests and the effect on the stability of a hydrogen-oxygen combustor was evaluated.

LIQUID PROPELLANT COMBUSTOR

Configuration and performance. - The basic configuration of the liquid propellant combustor, figure 1, is illustrated by the version used for photographic studies of jet burning (3, 4). The combustion chamber is a short cylindrical cavity 8 inches in diameter and 1/2 inch long. Liquid oxygen and gaseous hydrogen was injected radially from the circumference and the combustion gas flow was also radial. With this design, traveling transverse acous-

tics mode instability can be studied at reasonably low frequencies for a low thrust level combustor. The frequency is about 4500 cps for a thrust level of 100-200 pounds.

Injectors used in this configuration have given stable combustion during normal operation. It has always been possible to produce unstable operation, however, by tangential injection of secondary gas flow at the circumference. This secondary flow caused angular flow of the combustion gases and promoted unstable operation. The instability is attributed to the nonlinear behavior of a velocity sensitive combustion process (4).

Stability rating. - The degree of instability is related to the flow rate of secondary gas. Such a relation provides a method of rating the stability of an injector configuration or operating condition. One method of implementing this rating technique is to ramp the secondary flow rate and observe the change in dynamic behavior. A typical combustor test run is shown in figure 2. Gaseous nitrogen, the secondary gas normally used, is introduced after equilibrium combustion is established. The combustion pressure oscillations are shown to increase with an increase in secondary flow rate. This type of test gives both a threshold flow rate at the onset of instability and a relation between flow rate and pressure amplitude.

The effect on stability of a change in hydrogen flow rate at essentially constant oxygen flow rate for the injector used in the tests of aluminum injection is shown in figure 3. Pressure amplitude is shown as a function of tangential impulse of the secondary flow which theoretically determines the angular velocity. The threshold secondary flow rate for the onset of instability increases with an increase in hydrogen flow rate. It implies improved stability at high hydrogen flow rates. Pressure amplitude increases linearly with secondary flow rate in the low amplitude region. The three conditions of stability are resolved as three parallel lines - a characteristic to be used in interpreting the results of aluminum addition. This linear behavior is lost at higher pressure amplitudes, particularly when secondary flow rate increases the mean combustor pressure and affects the propellant flow rates.

Scaled versions of concentric tube injector elements for large thrust combustors were used in this study, figure 4. The stabilizing effect of high hydrogen flow rates observed with these elements is consistent with that for large thrust combustors. In the 20,000 pound thrust studies performed at the Lewis Research Center (5), a minimum hydrogen injection temperature for stable operation was used to rate for stability. The minimum temperature decreased with an increase in hydrogen flow rate. This implies improved stability. Such minimum temperatures cannot be directly compared to the tangential impulse units used for stability rating in this study. Stability of these concentric tube elements, however, can be related to the hydrogen injection pressure drop which controls the dynamic coupling between hydrogen flow rate and combustor pressure (6). Using equivalent pressure drop changes as a basis of comparing the two stability rating techniques, a 10° to 20° R decrease in the minimum hydrogen temperature is roughly comparable to an increase of 1 to 2 tangential impulse units.

ALUMINUM INJECTION TECHNIQUE

The experimental technique employed to inject aluminum into the liquid combustor was adapted from the solid propellant apparatus (1) shown in figure 5. The solid propellant is cast as a ring at the circumference of the chamber. Tangential gas injection is used to cause unstable operation. This secondary gas injection is supplied by a gas generator with a solid propellant charge shaped to give an increase in flow rate with time as indicated in figure 6 by the gas generator flow. Figure 6 shows a typical experimental test without aluminum addition from which a flow rate for the onset of instability and the increase in pressure amplitude with flow rate can be established. Small fractions of aluminum powder added to solid propellant in either the combustor or the gas generator completely suppressed this transverse mode instability. The result led to the conclusion about the particulate damping mechanism of aluminum powder and prompted the liquid combustor tests.

The technique of using a solid propellant gas generator to introduce aluminum particles in the secondary flow was adapted for the liquid combustor tests. An ammonium perchlorate and polybutadiene acrylic acid composition was used. The ratio of ground to unground oxidizer was varied to change the regression rate and ramping time of the secondary flow. For the aluminum addition tests, fine aluminum powder (5μ mean weight diameter) was added to the composition.

A comparison of the stability rating of the liquid combustor using gaseous nitrogen and the solid propellant gas generator without aluminum addition is shown in figure 7. The two gases give nearly identical results. The pressure amplitudes for a given tangential impulse are lower than those presented in figure 3. Secondary injection was along a chordal path for the figure 7 tests rather than the tangential path of the previous tests. Tangential injection of hot gases cause injector face burning which necessitated the use of a chordal path.

RESULTS AND DISCUSSION OF ALUMINUM INJECTION

Stability ratings of the liquid combustor using solid propellant gas generators with and without the 1/2 percent by weight aluminum addition are compared in figure 8. The predominant effect of aluminum addition is the reduction in amplitude for a given jet impulse. Data shown are from several tests in which the ramping rate of the secondary flow was varied. The agreement of results indicates that the response time of the unstable combustion system was not exceeded during ramping of the secondary flow. Although the mass faction of aluminum in the secondary flow was constant in these tests the mass faction of aluminum in the total flow rate varies with the ratio of secondary to primary flow rates. Mass percentage values of aluminum in the total propellant flow rate were calculated by simple mass averaging of flows for the experimental test conditions. These values are shown in figure 9 along the experimental line for 1/2 percent mass addition to the secondary flow. Mass percentages of aluminum in the total flow are less than 1/10 percent for the range of flows investigated.

Also shown in figure 9 is the experimental line for no aluminum addition and a series of constant mass fraction lines parallel to the no aluminum condition. These constant mass fraction lines represent one interpretation of the experimental results. It is based on the characteristic established in figure 3 where a change in stability caused by a change in hydrogen flow rate is resolved by such a parallel line characteristic. This interpretation of results shows that small addition of aluminum powder causes significant effects on stability. A 1/100 percent increase in the aluminum causes a change in stability equivalent to that of a 25 percent increase in hydrogen flow rate noted in figure 3. Using the comparison with the hydrogen temperature rating technique mentioned previously, a 1/100 percent increase in aluminum gives a stability change equivalent to 10° to 20° R decrease in hydrogen injection temperature.

The effect of such small changes in aluminum concentration on stability appears qualitatively consistent with the solid propellant combustor tests (1). The effect, however, differs substantially from results with metallized gelled propellants (7), where mass factions of aluminum of the order of 10 percent were needed to obtain measurable effects on stability. Either the stability of the two combustors differed greatly in their sensitivity to a change in damping or the aluminum was used less effectively for damping in the gelled propellants.

In the extrapolated low amplitude region of the experimental results, figure 9 shows that mass percentages of aluminum of less than 2/100 percent cause a reduction in stability. Although the reliability of the data in the low amplitude region is questionable, the result is consistent with some of the gelled metallized propellants (7). A destabilizing effect was noted at low concentrations under some conditions. The critical concentration, however, was about 20 percent rather than 2/100 percent.

The destabilizing effect may be postulated from previous photographic studies (3) which shown an oxygen jet length modulated by periodic variations in vaporization and erosion rates. Such modulations in the presence of a steady angular velocity provides a process for periodic energy addition (4). Aluminum particles dispersed in the gases acting on the jet may be expected to enhance this oscillatory mass removal process and increase the gains in the dynamic system. The enhanced process is visualized as a highly repetitive solid particle impingement on the liquid jet with subsequent mass removal with each impingement. The effect on stability would depend on the differences between such increased gains and the losses caused by particulate damping. A difference in the effect of particle concentration on gains and losses may be expected and could give a critical value of concentration which separates stabilizing from destabilizing concentrations of aluminum.

CONCLUSIONS

Secondary injection of aluminum powder was an effective method of suppressing transverse mode instability for the liquid oxygen and gaseous hydro-

gen propellant combination in a two-dimensional circular combustor. Stabilizing effects were observed for calculated mass percentages of aluminum in the total combustor gas flow above 2/100 percent. A destabilizing effect was noted at concentrations below 2/100 percent.

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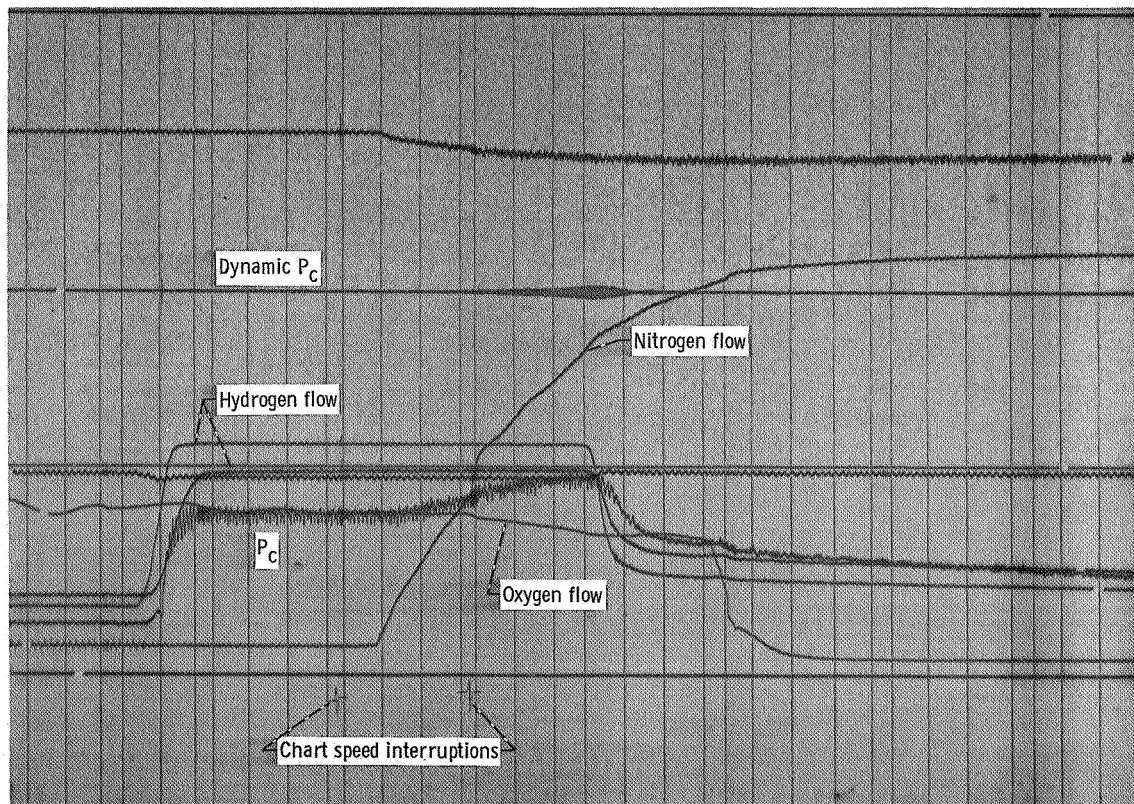
SYMBOLS

F jet thrust of secondary flow, lb

P_c combustor pressure, psia

$(\Delta P)_{pp}$ peak-to-peak pressure amplitude, psi

W_h hydrogen mass flow rate, lb/sec

W_o oxygen mass flow rate, lb/sec

W_T total mass flow rate within combustor, lb/sec
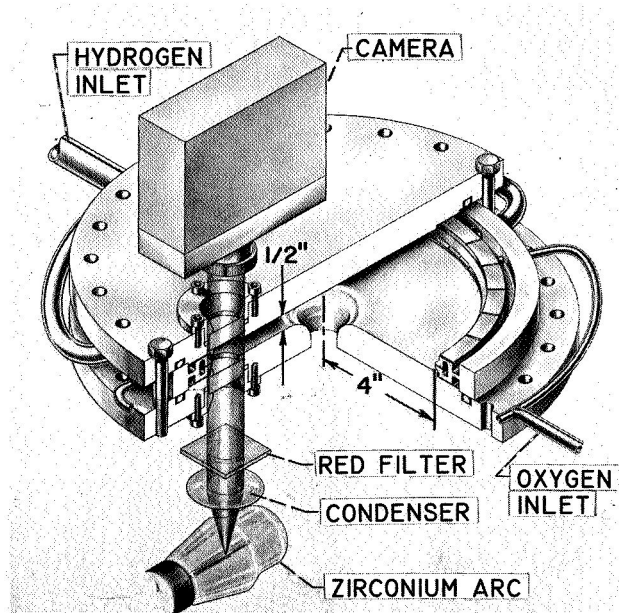
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Figure 1. – Two-dimensional circular combustor.

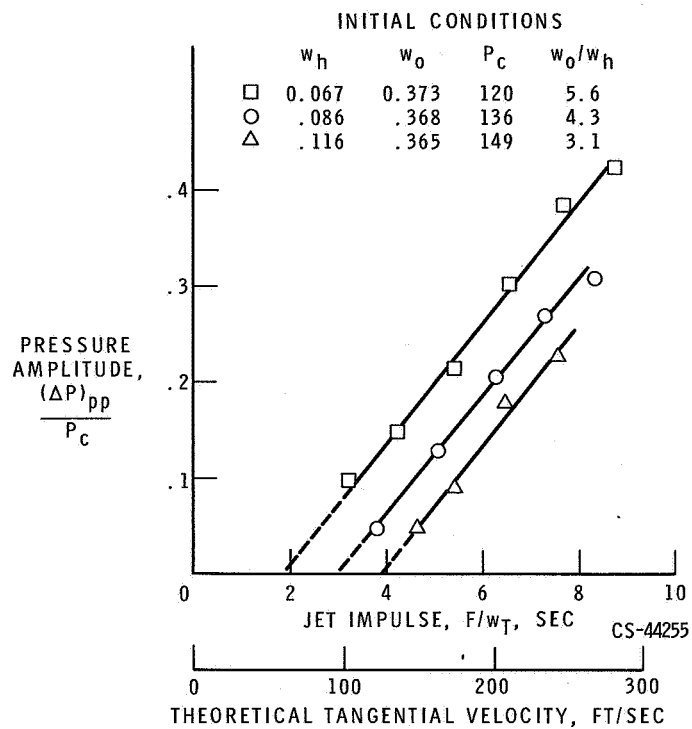CS-44256

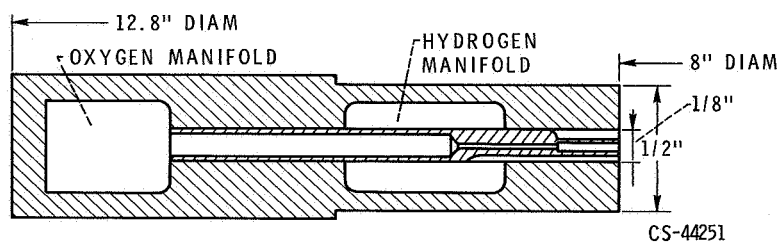Figure 2. – Experimental test for stability.

INITIAL CONDITIONS

	w_h	w_o	P_c	w_o/w_h
□	0.067	0.373	120	5.6
○	.086	.368	136	4.3
△	.116	.365	149	3.1

PRESSURE
AMPLITUDE,
$\dfrac{(\Delta P)_{pp}}{P_c}$

JET IMPULSE, F/w_T, SEC   CS-44255

THEORETICAL TANGENTIAL VELOCITY, FT/SEC

Figure 3. - Stability rating of three operating conditions.

12.8" DIAM

OXYGEN MANIFOLD

HYDROGEN
MANIFOLD

8" DIAM

1/8"

1/2"

CS-44251

HYDROGEN ANNULUS AREA	OXYGEN ORIFICE DIAM
0.0088 IN.^{2} EXIT	0.04 IN. EXIT
0.0033 IN.^{2} MIN	0.02 IN. MIN

24 ELEMENTS IN INJECTOR RING

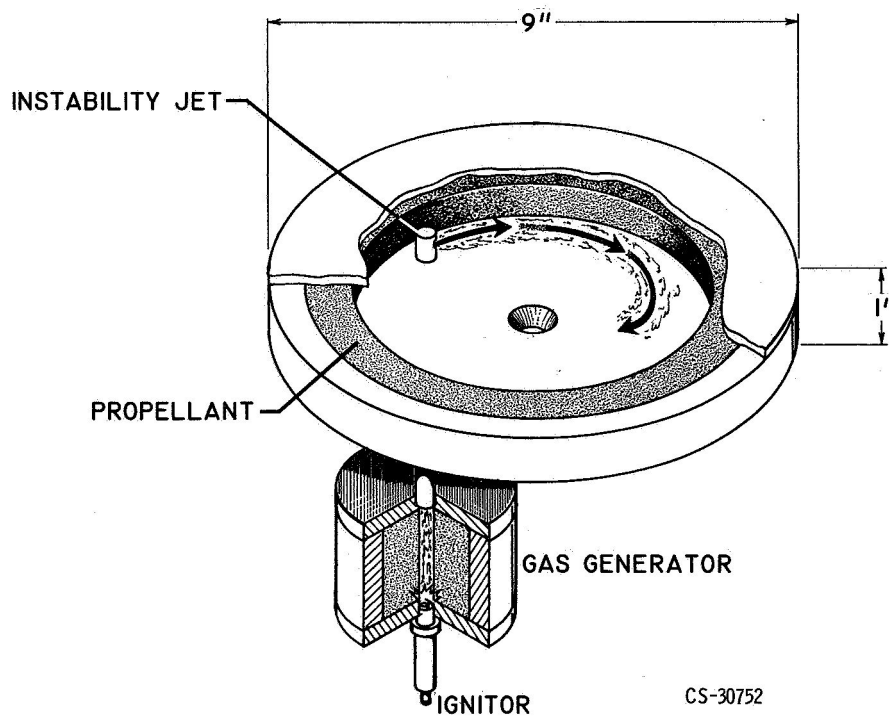Figure 4. - Concentric tube injector element.

9"

INSTABILITY JET

1"

PROPELLANT

GAS GENERATOR

IGNITOR

CS-30752

Figure 5. - Solid propellant combustor.

HIGH FREQUENCY CHANNEL

0.1 sec

10 MS
TIME

INCH

4

Gas generator flow

3

Signal
interference

Pc

2

Dynamic P_C

1

60 cps Timing mark

SEE INSERT

Time

CS-42066
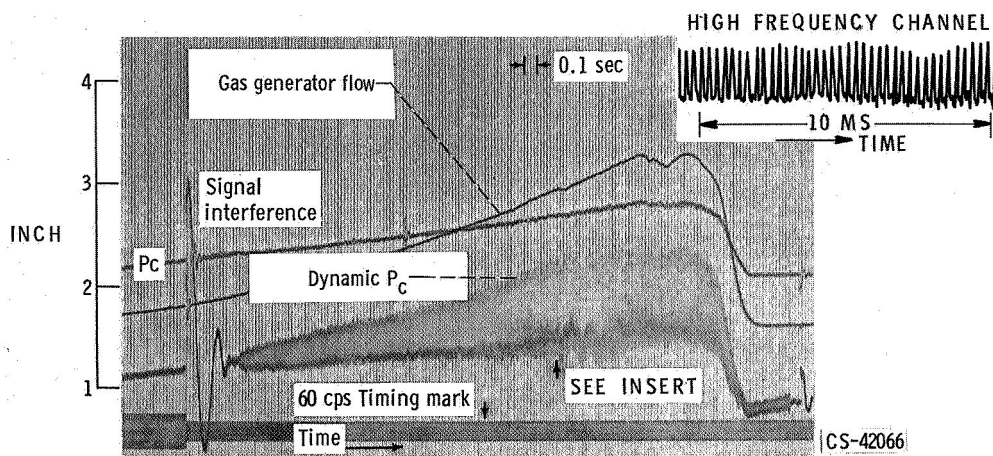
Figure 6. - Pressure-time trace without aluminum.

PRESSURE
AMPLITUDE,
$\dfrac{(\Delta P)_{pp}}{P_c}$

COMBUSTION GASES

NITROGEN

JET IMPULSE, F/w_T, SEC
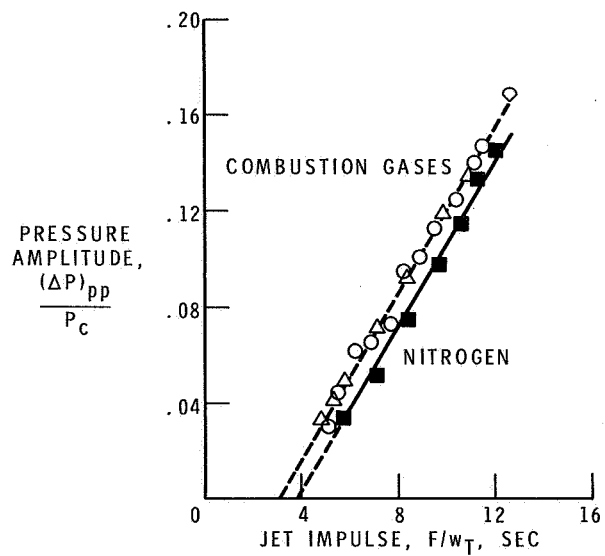
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Figure 7. – Effect of gas properties on stability rating.

PRESSURE
AMPLITUDE,
$\dfrac{(\Delta P)_{pp}}{P_c}$

NO ALUMINUM

ALUMINUM

JET IMPULSE, F/w_T, SEC
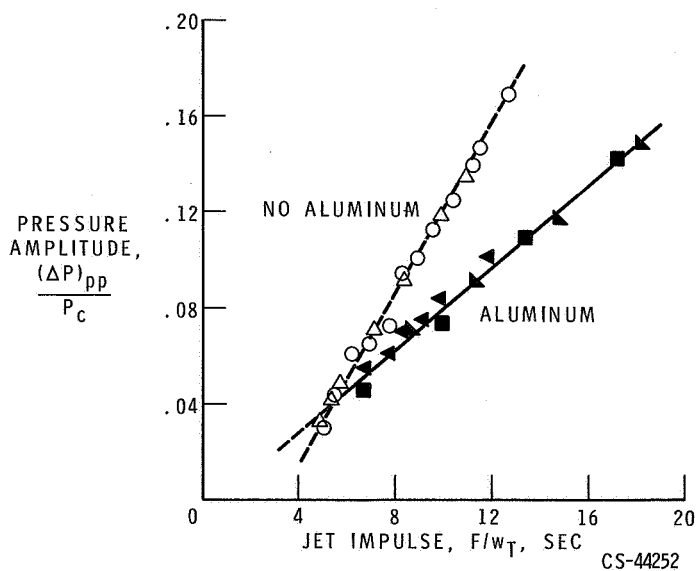
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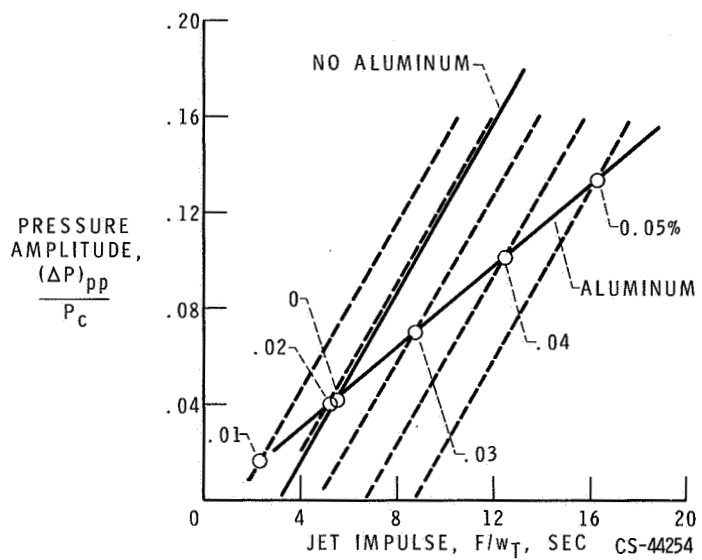Figure 8. – Effect of aluminum addition on stability rating.

Figure 9. - Indicated stability rating for aluminum addition.